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Buchanan, N., & Fusco, V. (2016). Pilot tone reference-less phase conjugator for phase modulated retrodirective antenna applications. *IEEE Antennas and Wireless Propagation Letters*, 15, 298-300.
<https://doi.org/10.1109/LAWP.2015.2442296>

Published in:
IEEE Antennas and Wireless Propagation Letters

Document Version:
Peer reviewed version

Queen's University Belfast - Research Portal:
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Pilot tone reference-less phase conjugator for phase modulated retrodirective antenna applications

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Abstract— This paper presents a simple tracking PLL which can be used to track phase modulated signals and provide a phase conjugated signal for retrodirective retransmission. The configuration allows the retrodirective antenna to directly track phase modulated signals with no requirement for a separate CW pilot tone. The ability to directly track phase modulated signals is carried out using a 4X multiplier on the tracking PLL reference signal. Practical phase conjugation results are presented for a 5 element retrodirective array simultaneously sending and receiving phase modulated (QPSK) signals. Signals with levels as low as -122 dBm can be phase conjugated and retransmitted with 30dBm EIRP.

Index Terms—Phased arrays, Phase modulation, Phase locked loops, Phase conjugation

I. INTRODUCTION

RETRODIRECTIVE antennas have many promising applications, for example, in satellite communications [1]. Satellite applications place a lot of challenges on the retrodirective antenna, namely weak received signal and complex modulation schemes. Recent retrodirective antennas [2] use a phase tracking PLL to track the phase of a weak received signal in the presence of a strong retransmitted signal. These systems are capable only of tracking CW signals, or modulation schemes such as amplitude shift keying, where there is no phase variation. QPSK signals can be tracked using a Costas loop [3], or a multiply, filter, divide architecture [4]. However these architectures are difficult to realise with discrete components and operation at low signal to noise ratios can be problematical.

In this paper we describe a tracking PLL architecture capable of tracking QPSK signals, as well as more complex schemes up to 256 QAM. The proposed phase locked loop is no more complicated, in terms of component count, than a basic CW tracking PLL and is capable of simultaneously phase conjugating received signals as low as -122 dBm, in the presence of retransmitting a signal with an EIRP of up to 30 dBm.

II. PHASE MODULATION TRACKING PHASED LOCKED LOOP

The phase modulation Tracking Phased Locked Loop (PLL) shown in Fig. 1 is an adaption of a classical phaselock receiver [5]. The main change proposed to the phaselock receiver is making the reference signal presented to the phase detector 4 times the frequency of the intermediate frequency signal (F_{IF}) it is being locked to. The operation of the PLL is explained with reference to the timing diagram in Fig. 2. Here the reference signal, and a QPSK signal are shown, as square waves, assuming a limiting operation within the EXOR phase detector. Referring to Fig. 2(a), the reference signal is shown as a square wave of 4X the frequency of the IF signal. Scenario (i) shows the output of the phase detector (Exclusive OR operation), with no phase lag applied to the IF signal. This phase detector output is passed through a loop filter to produce an average DC signal, shown as the dotted line Fig. 2(a). Scenario (ii) in Fig. 2(a) shows the effect when the IF signal has a phase lag, this is equivalent to angle of arrival changing in an antenna array. When the phase lag is present an additional pulse starts to appear which raises the average DC level of the phase detector output. This would have the effect, in the PLL of Fig. 1, to momentarily shift the frequency of the VCO until the IF is again locked in phase to the reference signal. It is important that the IF square wave has a slightly shorter “on” state than “off” state. This is necessary to avoid a second pulse appearing on the falling edge of the IF signal, since this would cancel the effect of the pulse generated from the leading edge. A slightly shorter “on” time than “off” time is produced by the phase detector IF input [6] threshold levels. The IF input recognises an “on” state as $>0.2V$ and anything below this as an “off” state. If the phase detector is being driven by a sine wave signal of 1V p-p, or $\pm 0.5V$, the phase detector internal IF waveform will transition the $\pm 0.5V$ input signal to the “on” state at 0.2V resulting in a square wave with an unequal duty cycle with shorter “on” state compared to “off” state.

Fig. 2(b) shows the actual waveforms obtained from the experimental setup of Fig. 1. Note that reference and IF waveforms appear sinusoidal since limiting action is internal to the phase detector and cannot be directly measured. From Fig.

2, if the IF phase was to be shifted by 0° , 90° , 180° or 270° then the IF signal would always have the same relationship to the reference signal, since one cycle of the reference signal is equivalent to a 90° shift in the IF waveform. This has the result that the DC output of the phase detector is unchanged with the four 90° states of QPSK modulation.

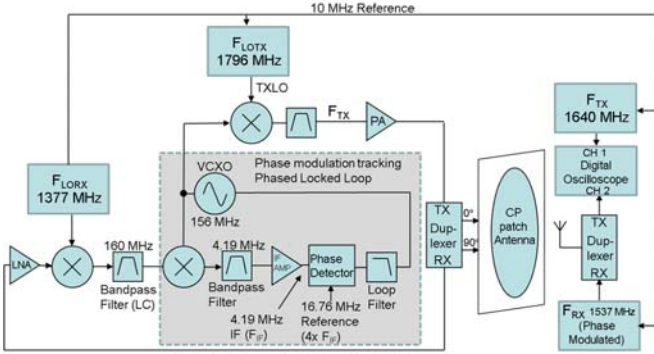


Fig. 1. Phase Locked Loop for phase modulation tracking

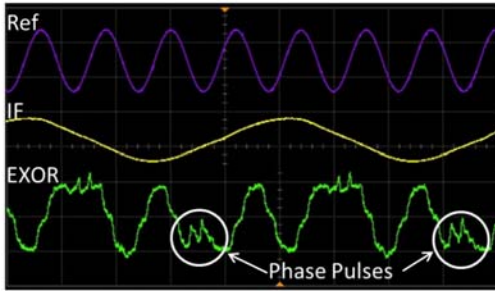
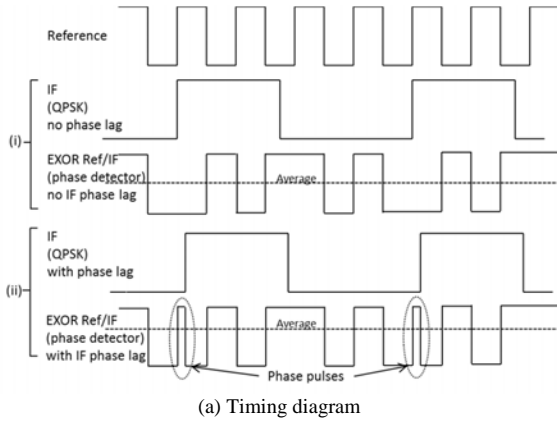


Fig. 2. Phase Detector Waveforms

III. EXPERIMENTAL RESULTS

A. Phase conjugating results

A phase conjugating cell has been designed (Fig. 1) and employs a double superheterodyne receiver/transmitter arrangement to allow it to operate with the high level of specification required for satellite communication systems with regards to image rejection, selectivity, and so on. The module operates at L band with a receive frequency in the 1.5 GHz

range, and transmit frequency in the 1.6 GHz range. The PLL loop filter design is critical to obtain low phase noise and jitter on the output signal [7]. To provide stable performance to low signal levels, a 2nd order active loop filter was used with a cutoff frequency of 100 Hz. Another critical component for low signal level operation in the receiver chain is the LNA, which has a gain of $>20\text{dB}$ with a noise figure of $<2\text{dB}$. The mixers used were active types, typically having conversion gains in the region of 10dB and noise figures of around 5dB .

A phase modulated transmit signal of 20kbps is chosen to provide an optimum match to the module's IF filters. A 1377.73 MHz local oscillator is used for the receiver section, which down converts to a first IF of 160.19 MHz . This is then further down converted to a second IF of 4.19 MHz by mixing with a 156 MHz VCXO, which forms part of the phase tracking circuit. The 156 MHz VCXO tracks the phase of the received signal, and is up converted by mixing with a TX LO signal of 1796 MHz . This up converting action of $F_{LO} - F_{VCXO} = F_{TX}$, provides the phase conjugation for the retransmit signal.

The resultant IF signal time domain waveforms, taken from the inputs to the phase detector (Fig. 1), allow all the four phase states of the QPSK signal to be captured is shown in Fig. 3. Each of the four QPSK phase states bears the same phase relationship to the reference signal, thus providing a stable average output of the phase detector, after low pass filtering.

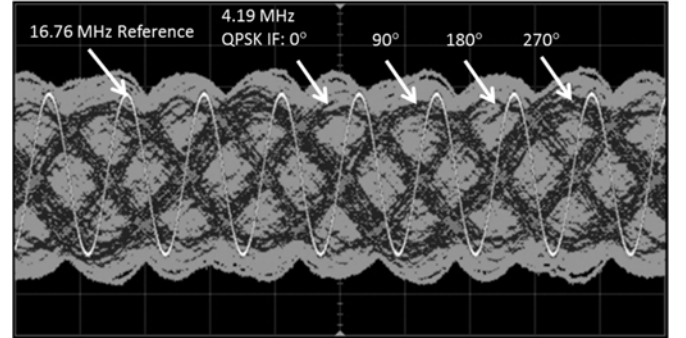


Fig. 3. Reference and QPSK IF time domain waveforms

The phase conjugating cell was measured down to low received signal levels using the setup of Fig. 1. The received signal level at the antenna was determined accurately from the IF signal amplitude output of the 4.19 MHz IF amplifier, since the conversion gain, from the RX port to IF output, of the phase conjugating cell had been previously measured. Accurate phase conjugation of QPSK to -122dBm , 16QAM to -121 dBm , and 256 QAM down to -119dBm was obtained (Fig 4). The retransmitted EIRP of a single antenna module with 6.5dBi CP antenna is about 30 dBm making the arrangement presented here viable for applications such as Inmarsat BGAN [1] where the received signal strengths of the spot beams are in the region of -110 dBm at the antenna, and retransmit EIRP in the region of 38 dBm , i.e. 6 modules each with a retransmit EIRP of 30dBm .

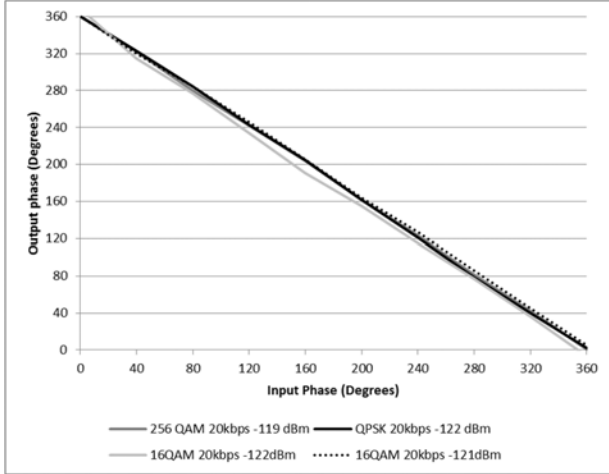


Fig. 4. Reference and QPSK IF time domain waveforms

B. Retrodirective measurements – Transmit Mode

The antenna element setup of Fig. 1 was configured as a 5x1 element retrodirective array, operating in full QPSK duplex transmit/receive mode and its monostatic radiation patterns measured by applying a QPSK received signal to the array and measuring the QPSK modulated retransmitted signal. A QPSK modulated signal was applied to the TXLO port (Fig. 1). The transmitted radiation pattern was measured with regard to the retransmitted Error Vector Magnitude (EVM), rather than retransmitted amplitude, Fig. 5, since EVM is a more suitable benchmark for retransmitted modulated signal quality, ensuring that all transmitted symbols are correctly aligned across the array. Measured single element EVM is approximately 2% higher than that of the 5 element array. With all five elements switched on a flat 5% EVM versus azimuth response is obtained over the azimuth range $\pm 40^\circ$, a 5% EVM equates to a BER of less than 10^{-6} [8] for QPSK.

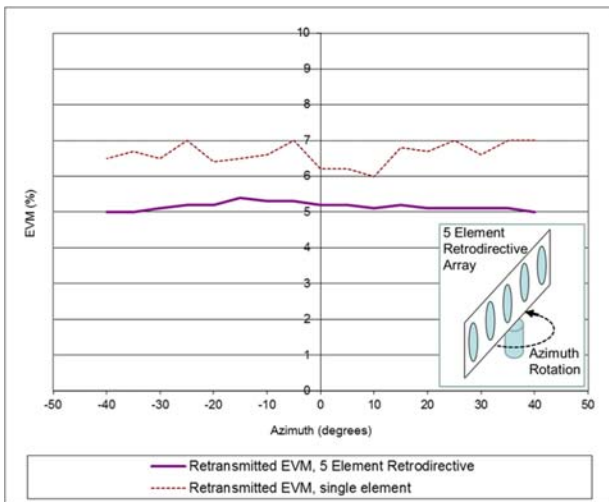


Fig. 5. Retrasmited EVM Vs azimuth for 5 element retrodirective array

C. Retrodirective measurements – Receive Mode

The retrodirective array was shown practically to have the ability to optimally combine the received signal. The method used involves combining a constant phase IF signal from each element, such that the IFs always combine in phase regardless of angle of arrival. This mode of operation follows the principles of [9], with the exception that, in this case, phase modulated signals can be used instead of CW signals. A fairly flat EVM response for the array was achieved on receive mode, varying from 6.2% to 7.2% over for an azimuth range of -40° to 40° , confirming optimal phase combination on receive mode over a wide azimuth range.

IV. CONCLUSIONS

The retrodirective antenna has been shown to directly track QPSK/16QAM/256QAM signals of levels as low as -122 dBm whilst being able to simultaneously transmit/receive digital modulation. The tracking PLL configuration used within the retrodirective antenna is no more complex than a conventional phaselock receiver requiring only the addition of a 4X multiplier on the reference signal.

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